Large pseudo-scalar components in the C2HDM

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We discuss the CP nature of the Yukawa couplings of the Higgs boson in the framework of a complex two Higgs doublet model (C2HDM). After analysing all data gathered during the Large Hadron Collider run 1, the measurement of the Higgs couplings to the remaining SM particles already restricts the parameter space of many extensions of the SM. However, there is still room for very large CP-odd Yukawa couplings to light quarks and leptons while the top-quark Yukawa coupling is already very constrained by current data. Although indirect measurements of electric dipole moments play a very important role in constraining the pseudo-scalar components of the Yukawa couplings, we argue that a direct measurement of the ratio of pseudoscalar to scalar couplings should be one of the top priorities for the LHC run 2.

I. INTRODUCTION

The Higgs boson discovery by the ATLAS [1] and CMS [2] collaborations at the Large Hadron Collider (LHC) has triggered a number of studies on multi-Higgs extension of the Standard Model (SM). Although the measured Higgs couplings show a very good agreement with the SM predictions there is still room for interesting non-SM features to be explored at the next LHC run. In fact, many multi-Higgs models provide interesting scenarios as is the case of the complex two-Higgs double model (C2HDM). The 2HDM was proposed by T. D. Lee [3] as a means to explain the matter-antimatter asymmetry of the universe by allowing for an extra source of CP-violation in the potential (see [4, 5] for a review). The existing experimental data and in particular the one recently analysed at the LHC has been used in several studies with the goal of constraining the parameter space of the C2HDM [6–9] or just the Yukawa couplings [10].

In this work we analyse C2HDM scenarios where the scalar component of the SM-like Higgs Yukawa couplings to down-type quarks or to leptons vanish. The corresponding CP-odd component has to be non-zero for the model to be in agreement with the LHC results. We will also discuss situations where the Yukawa coupling is shared by the CP-even and CP-odd components of the Higgs boson. Our approach is driven both by the current measurements and by the predictions for the next LHC run. The processes $pp \to h \to WW(ZZ)$, $pp \to h \to \gamma\gamma$ and $pp \to h \to \tau^+\tau^-$ are at present measured with an accuracy of about 20%. The expected accuracies for the signal strengths of different Higgs decay modes were presented by the ATLAS [11] and CMS [12] collaborations (see also [13]) for $\sqrt{s} = 14$ TeV and for 300 and 3000 fb^{-1} of integrated luminosities. The predictions for the signal strengths with the final states VV, $\gamma\gamma$ and $\tau^+\tau^-$ will be used to understand how the model will perform at the end of the next LHC run because as shown in [9] they reproduce quantitatively the effect of all possible final states in the Higgs decay. Therefore, the predicted accuracies for the signal strength lead us to consider situations where, at 13 TeV, the rates are measured within either 10% or 5% of the SM prediction. We note that there is no visible difference in the plots when the energy is changed from 13 to 14 TeV as discussed in [9].

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II. THE C2HDM

The allowed parameter space of the C2HDM was recently reviewed in [14] (see also [6, 9, 15–20]). In this section we will briefly describe the C2HDM, a complex 2HDM with a softly broken Z_2 symmetry $\phi_1 \to \phi_1, \phi_2 \to -\phi_2$. We write the scalar potential as [5]

$$
\begin{aligned}
V_H \;=\; & m_{11}^2 |\phi_1|^2 + m_{22}^2 |\phi_2|^2 - m_{12}^2 \, \phi_1^\dagger \phi_2 - (m_{12}^2)^* \, \phi_2^\dagger \phi_1 \\[4pt]
& + \frac{\lambda_1}{2} |\phi_1|^4 + \frac{\lambda_2}{2} |\phi_2|^4 + \lambda_3 |\phi_1|^2 |\phi_2|^2 + \lambda_4 \, (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) \\[4pt]
& + \frac{\lambda_5}{2} (\phi_1^\dagger \phi_2)^2 + \frac{\lambda_5^*}{2} (\phi_2^\dagger \phi_1)^2 ,
\end{aligned}
\tag{1}
$$

where all couplings except m_{12}^2 and λ_5 are real due to the hermiticity of the potential and $\arg(\lambda_5) \neq 2\arg(m_{12}^2)$, so that the two phases cannot be removed simultaneously [15].

We work in a basis where the vacuum expectation values (vevs) are real. The corresponding CP-conserving 2HDM, is obtained from the C2HDM by taking m_{12}^2 and λ_5 real. Defining the scalar doublets as

$$
\phi_1 = \begin{pmatrix} \varphi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \eta_1 + i\chi_1) \end{pmatrix}, \qquad
\phi_2 = \begin{pmatrix} \varphi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \eta_2 + i\chi_2) \end{pmatrix},
\tag{2}
$$

with $v = \sqrt{v_1^2 + v_2^2} = (\sqrt{2} G_\mu)^{-1/2} = 246$ GeV, they can be written in the Higgs basis as [21, 22]

$$
\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix},
\tag{3}
$$

where $\tan\beta = v_2/v_1$, $c_\beta = \cos\beta$, and $s_\beta = \sin\beta$. In the Higgs basis the second doublet does not get a vev and the Goldstone bosons are in the first doublet.

Defining η_3 as the neutral imaginary component of the H_2 doublet, the mass eigenstates are obtained from the three neutral states via the rotation matrix R

$$
\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix}
\tag{4}
$$

which will diagonalize the mass matrix of the neutral states via

$$
R \, \mathcal{M}^2 \, R^T = \mathrm{diag}\left(m_1^2, m_2^2, m_3^2\right),
\tag{5}
$$

and $m_1 \leq m_2 \leq m_3$ are the masses of the neutral Higgs particles. We parametrize the mixing matrix R as [17]

$$
R = \begin{pmatrix}
c_1 c_2 & s_1 c_2 & s_2 \\
-(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\
-c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3
\end{pmatrix}
\tag{6}
$$

with $s_i = \sin\alpha_i$ and $c_i = \cos\alpha_i$ $(i = 1, 2, 3)$ and

$$
-\pi/2 < \alpha_1 \leq \pi/2, \qquad -\pi/2 < \alpha_2 \leq \pi/2, \qquad -\pi/2 \leq \alpha_3 \leq \pi/2.
\tag{7}
$$

We choose the 9 independent parameters of the C2HDM to be v, $\tan\beta$, $m_{H^\pm}$, α_1, α_2, α_3, m_1, m_2, and $\mathrm{Re}(m_{12}^2)$. The mass of the heavier neutral scalar is a dependent parameter given by

$$
m_3^2 = \frac{m_1^2 R_{13}(R_{12} \tan\beta - R_{11}) + m_2^2 R_{23}(R_{22} \tan\beta - R_{21})}{R_{33}(R_{31} - R_{32} \tan\beta)}.
\tag{8}
$$

The parameter space will be constrained by the condition $m_3 > m_2$.

The Higgs coupling to gauge bosons is [6]

$$
C = c_\beta R_{11} + s_\beta R_{12} = \cos(\alpha_2) \cos(\alpha_1 - \beta).
\tag{9}
$$

Regarding the Yukawa couplings, the Z_2 symmetry is extended to the Yukawa Lagrangian [23] to avoid flavour changing neutral currents (FCNC). The up-type quarks couple to ϕ_2 and the usual four models are obtained by coupling down-type quarks and charged leptons to ϕ_2 (Type I) or to ϕ_1 (Type II); or by coupling the down-type quarks to ϕ_1 and the charged leptons to ϕ_2 (Flipped) or finally by coupling the down-type quarks to ϕ_2 and the charged leptons to ϕ_1 (Lepton Specific). The Yukawa couplings can then be written, relative to the SM ones, as $a + ib\gamma_5$ with the coefficients presented in table I.

	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta} \gamma_5$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta} \gamma_5$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta} \gamma_5$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta} \gamma_5$
Down	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta} \gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta} \gamma_5$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta} \gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta} \gamma_5$
Leptons	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta} \gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta} \gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta} \gamma_5$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta} \gamma_5$

TABLE I: Yukawa couplings of the lightest scalar, h_1, in the form $a + ib\gamma_5$.

III.   RESULTS AND DISCUSSION

In order to perform our analysis we generate points in parameter space in the following intervals: the lightest neutral scalar is $m_1 = 125$ GeV [1], the angles $\alpha_{1,2,3}$ all vary in the interval $[-\pi/2, \pi/2]$, $1 \leq \tan\beta \leq 30$, $m_1 \leq m_2 \leq 900\,\text{GeV}$ and $-(900\,\text{GeV})^2 \leq Re(m_{12}^2) \leq (900\,\text{GeV})^2$. The points are generated randomly subject to the following constraints,

- **B-physics** - $b \to s\gamma$, in Type II/F we choose the range for the charged Higgs mass as $340\,\text{GeV} \leq m_{H^\pm} \leq 900\,\text{GeV}$ [26], while in Type I/LS the range is $100\,\text{GeV} \leq m_{H^\pm} \leq 900\,\text{GeV}$. The remaining constraints from B-physics [27, 28] (and from the $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ [29] measurement) force $\tan\beta \gtrsim 1$ for all models;

- **LEP** - The charged Higgs mass is above 100 GeV due to LEP searches on $e^+e^- \to H^+H^-$ [30] (we also consider the LHC results on $pp \to \bar{t}t(\to H^+\bar{b})$ [31, 32]). Very light neutral scalars are also constrained by LEP results [33];

- **LHC - bounds on heavy scalars** - The most relevant searches for the C2HDM are $pp \to \phi \to W^+W^-(ZZ)$ [34, 35] and $pp \to \phi \to \tau^+\tau^-$ [36, 37], where ϕ is a spin zero particle;

- **Theoretical constraints** - the potential is bounded from below [38], perturbative unitarity is enforced [39–41] and all allowed points conform to the oblique radiative parameters [42–44].

Finally we consider the results stemming from the the 125 GeV Higgs couplings measurements. The signal strength is defined as

$$\mu_f^{h_i} = \frac{\sigma \, \text{BR}(h_i \to f)}{\sigma^{\text{SM}} \, \text{BR}^{\text{SM}}(h_i \to f)} \tag{10}$$

where σ is the Higgs boson production cross section and $\text{BR}(h_i \to f)$ is the branching ratio of the h_i decay into the final state f; σ^{SM} and $\text{BR}^{\text{SM}}(h \to f)$ are the respective quantities calculated in the SM. Values for the cross sections were obtained from: HIGLU [45] - gluon fusion at NNLO, together with the corresponding expressions for the CP-violating model in [9]; SusHi [46] - $b\bar{b} \to h$ at NNLO; [47] - Vh (associated production), $t\bar{t}h$ and $VV \to h$ (vector boson fusion). As previously discussed, we will force μ_{VV}, $\mu_{\gamma\gamma}$ and $\mu_{\tau\tau}$ to be within 20% of the expected SM value, which at present roughly matches the average precision at 1σ. Taking all other processes into account has no significant impact on the results as shown in [9].

In the C2HDM there is only one way to obtain pure scalar states. When we set $s_2 = 0$ we get $R_{13} = 0$ and all pseudoscalar components vanish. However, depending on the model type, there are in principle two ways to obtain a vanishing scalar component. One is by setting $R_{12} = 0$. However, as shown in figure 1 (middle), values of $R_{12} \approx 0$ are excluded when all constraints are taken into account. The other possibility is to have $R_{11} = c_1\,c_2 = 0$ which is still allowed as shown in figure 1 (left). This can be obtained by setting either $c_2 = 0$ or $c_1 = 0$. $c_2 = 0$ is excluded as it would mean $g_{h_1 VV} = 0$, where V is a massive vector boson. Finally we can choose $c_1 = 0$. The values for a_F and b_F ($F = U, D, L$) in this scenario are presented in Table II.

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[1] The latest results on the measurement of the Higgs mass are 125.36 ± 0.37 GeV from ATLAS [24] and $125.02 + 0.26 - 0.27$ (stat) $+0.14 - 0.15$ (syst) GeV from CMS [25].
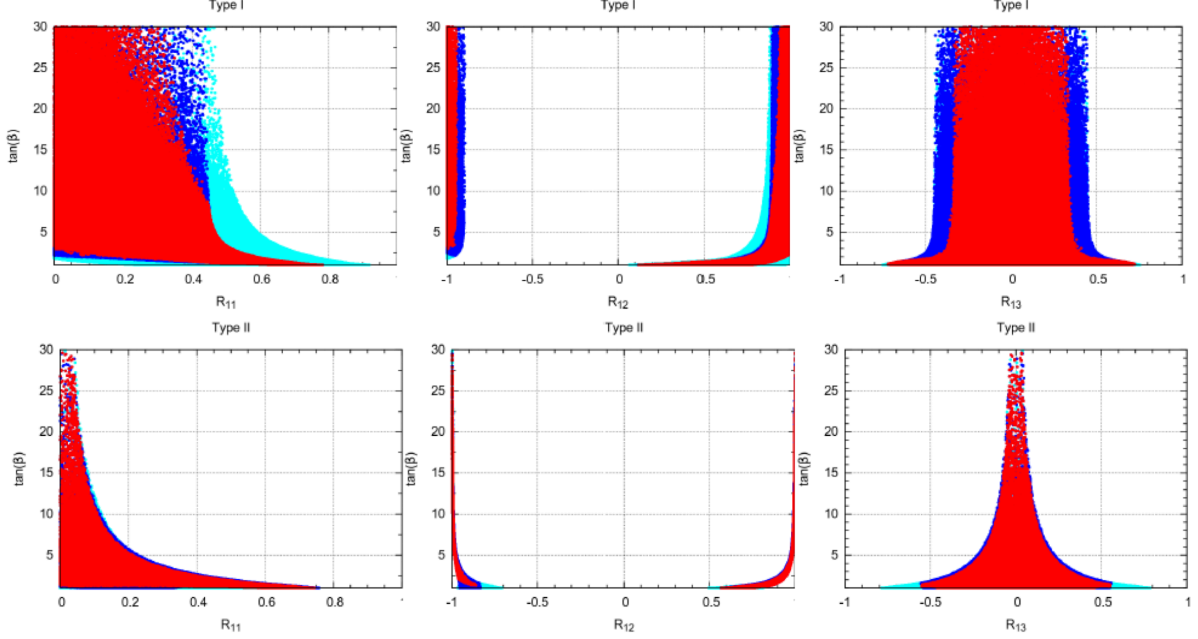
FIG. 1: Top: $\tan\beta$ as a function of R_{11} (left), R_{12} (middle) and R_{13} for Type I. Bottom: same but for Type II. The rates are taken to be within 20% of the SM predictions. The colours are superimposed with cyan/light-grey for μ_{VV}, blue/black for $\mu_{\tau\tau}$ and finally red/dark-grey for $\mu_{\gamma\gamma}$ with $\sqrt{s} = 8$ TeV.

Type I	$a_U = a_D = a_L = \frac{c_2}{s_\beta}$	$b_U = -b_D = -b_L = -\frac{s_2}{t_\beta}$
Type II	$a_D = a_L = 0$	$b_D = b_L = -s_2\,t_\beta$
Type F	$a_D = 0$	$b_D = -s_2\,t_\beta$
Type LS	$a_L = 0$	$b_L = -s_2\,t_\beta$

TABLE II: a_F and b_F limits for $c_1 = 0$ for the four model types.

As shown in table II the scenarios where the scalar component vanishes arise only in models Type II, F and LS. In Type II one can have $a_D = a_L = 0$ while in F (LS) only $a_D = 0$ ($a_L = 0$) is possible. In this scenario the coupling to gauge bosons is

$$C^2 = s_\beta^2 c_2^2\,. \tag{11}$$

Note that even if $s_2 = 0$ the pseudoscalar component can still be large due to a large value of $\tan\beta$.

We will now discuss in detail the allowed parameter space in the (a_F, b_F) plane for the different model types. We will plot $\mathrm{sgn}(C)\,a_F$ ($\mathrm{sgn}(C)\,b_F$) instead of a_F (b_F) with $F = U, D, L$, to avoid the dependence on the phase conventions in choosing the range for the angles α_i. In the left panel of figure 2 we show $b_D = b_L$ as a function of $a_D = a_L$ for Type II and $\sqrt{s} = 13$ TeV with all rates at 10% (blue/black), 5% (red/dark-grey), and 1% (cyan/light-grey). We start by noting that this scenario is still possible with the rates within 5% of the SM value at the LHC and at $\sqrt{s} = 13$ TeV. This scenario can only be excluded by a measurement of the rates if the accuracy reaches about 1%. The constraints on the model force $|b_D| \to 1$ when $|a_D| \to 0$. When $|b_D| \approx 1$, the couplings of the up-type quarks to the lightest Higgs have the form

$$a_U^2 = (1 - s_2^4) = (1 - 1/t_\beta^4), \quad b_U^2 = s_2^4 = 1/t_\beta^4, \tag{12}$$

while the coupling to massive gauge bosons is now

$$C^2 = (t_\beta^2 - 1)/(t_\beta^2 + 1) = (1 - s_2^2)/(1 + s_2^2)\,. \tag{13}$$

In the right panel of figure 2 we show b_U as a function of a_U for Type II with the same colour code. We conclude from the plot that the constraint on the values of (a_U, b_U) are already quite strong and will be much stronger in the future just taking into account the measurement of the rates.
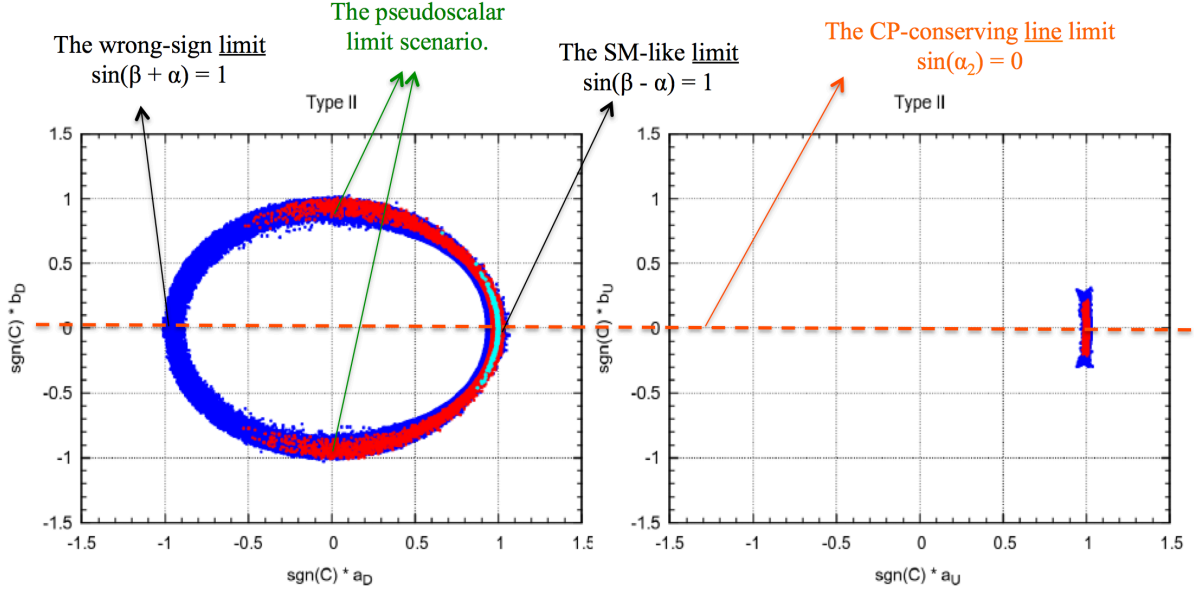
FIG. 2: Left: $\text{sgn}(C)\, b_D = \text{sgn}(C)\, b_L$ as a function of $\text{sgn}(C)\, a_D = \text{sgn}(C)\, a_L$ for Type II and a center of mass energy of 13 TeV with all rates at 10% (blue/black), 5% (red/dark-grey), and 1% (cyan/light-grey). Right: same, but for $\text{sgn}(C)\, b_U$ as a function of $\text{sgn}(C)\, a_U$.
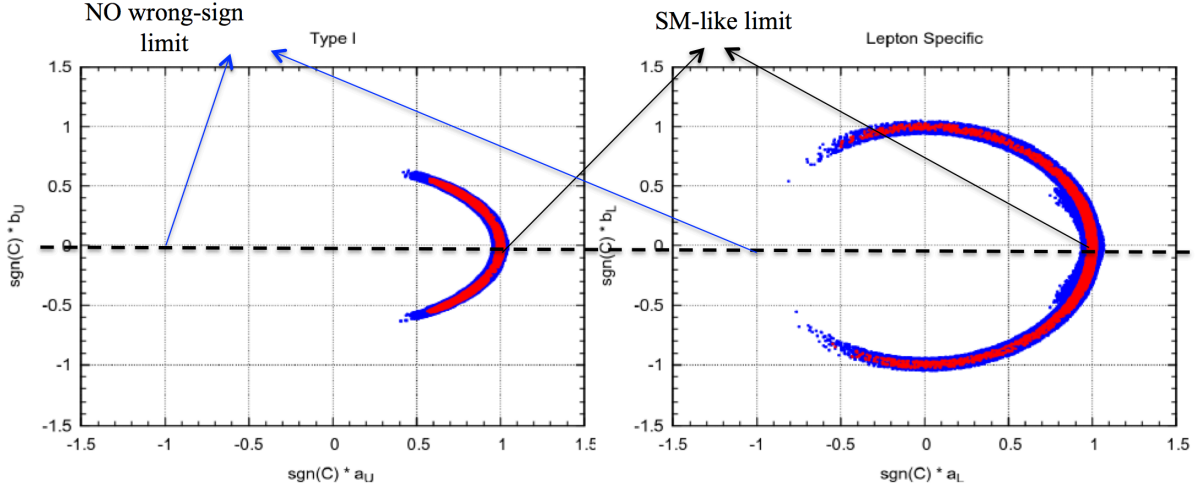

FIG. 3: Left: $\text{sgn}(C)\, b_U$ as a function of $\text{sgn}(C)\, a_U$ for Type I and a center of mass energy of 13 TeV with all rates at 10% (blue/black) and 5% (red/dark-grey). Right: $\text{sgn}(C)\, b_L$ as a function of $\text{sgn}(C)\, a_L$ for LS and a center of mass energy of 13 TeV with all rates at 10% (blue/black) and 5% (red/dark-grey).

In the left panel of figure 3 we show b_U as a function of a_U for Type I and $\sqrt{s} = 13$ TeV with all rates at 10% (blue/black) and 5% (red/dark-grey). We should point out that even at 10% there are still allowed points close to $(a, b) = (0.5, 0.6)$ with no dramatic changes occurring for an increase in accuracy to 5%. In the right panel we present b_L as a function of a_L for Type LS with the same colour code. Here again the $(a_L, b_L) = (0, 1)$ scenario is still allowed with both 10% and 5% accuracy. However, as was previously shown, the wrong sign limit is not allowed for the LS model [48, 49]. Nevertheless, in the C2HDM, the scalar component $\text{sgn}(C)\, a_L$ can reach values close to -0.8. Finally, for the up-type and down-type quarks, the plots are very similar to the one in the right panel of figure 2 for Type II.

In the left panel of figure 4 we present the allowed space in the $\sin\alpha_2$-$\tan\beta$ plane, for Type II and $\sqrt{s} = 13$ TeV. Rates at 10% are shown in blue/black while in red/dark-grey we present the points with $|a_D| < 0.1$ and $||b_D| - 1| < 0.1$ and in green $|b_D| < 0.05$ and $||a_D| - 1| < 0.05$. The right panel now shows the allowed space in the $\sin\alpha_2$-$\cos\alpha_1$ plane. The purpose of these plots is to pinpoint the main differences between the SM-like
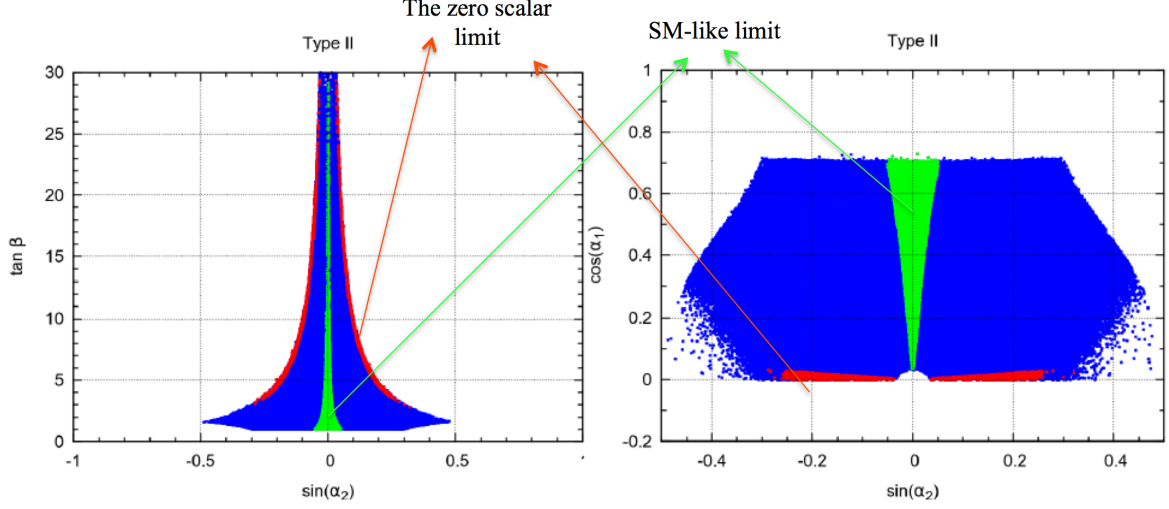
FIG. 4: Left: $\tan\beta$ as a function of $\sin\alpha_2$ for Type II and a center of mass energy of 13 TeV with all rates at 10% (blue/black). In red/dark-grey we show the points with $|a_D| < 0.1$ and $||b_D| - 1| < 0.1$ and in green $|b_D| < 0.05$ and $||a_D| - 1| < 0.05$ Right: same, with $\tan\beta$ replaced by $\cos\alpha_1$.

scenario, where $(|a_D|, |b_D|) \approx (1, 0)$ and the pseudoscalar scenario where $(|a_D|, |b_D|) \approx (0, 1)$. In the SM-like scenario $\sin\alpha_2 \approx 0$, $\tan\beta$ is not constrained and the allowed values of $\sin\alpha_2$ grow with increasing $\cos\alpha_1$. In the pseudoscalar scenario $\cos\alpha_1 \approx 0$, $\sin\alpha_2$ and $\tan\beta$ are strongly correlated and $\tan\beta$ has to be above ≈ 3. We note that all values of a_D and b_D are allowed provided $a_D^2 + b_D^2 \approx 1$.

A. Direct measurements of the CP-violating angle

We have seen that the precise measurements of the Higgs couplings allows us to constrain both the scalar and the pseudoscalar Yukawas in the C2HDM. However, a direct measurement of the relative size of the pseudoscalar to scalar coupling is important because it directly probes the Higgs couplings to light quarks and leptons. Moreover, when combined with EDMs it can provide universality tests for the CP-odd components of the Yukawas.

The angle that measures the pseudoscalar to scalar ratio, ϕ_i, is defined by

$$\tan\phi_i = b_i/a_i \qquad i = U, D, L,\tag{14}$$

and could in principle be measured for all Yukawa couplings. Direct measurements of this ratio in the up-quark sector, b_U/a_U, was first proposed in [50] and more recently in [51–53]. The process $pp \to hjj$ [54] also allows to probe the same vertex as discussed in [55, 56]. In reference [56] an exclusion of $\phi_t > 40°$ ($\phi_t > 25°$) for a luminosity of 50 fb^{-1} (300 fb^{-1}) was obtained for 14 TeV and assuming $\phi_t = 0$ as the null hypothesis. A study of the $\tau^+\tau^-h$ vertex was proposed in [57] (see also [58, 59]) and a detailed study taking into account the main backgrounds [60] lead to an estimate in the precision of $\Delta\phi_\tau$ of 27° (14.3°) for a luminosity of 150 fb^{-1} (500 fb^{-1}) and $\sqrt{s} = 14$ Tev.

The number of independent measurements of ϕ_i one needs depends on the C2HDM Yukawa type. For Type I one process is enough since $\phi_U = \phi_D = \phi_L$. For all other types we need two independent measurements. For type II and LS the planned measurements of ϕ_t and ϕ_τ would be enough while for type F we would need ϕ_b. Incompatibility in the measured values of ϕ_t and ϕ_τ would exclude both Type I and F.

We will now discuss the behaviour of $\cos\alpha_1$ (figure 5 left) and $\text{sgn}(C)\, a_D$ (figure 5 right) as a function of $\phi_D = \phi_\tau$ for Type II. In figure 5 $\sqrt{s} = 13$ TeV and all rates are taken at 10% (blue/black); in red/dark-grey we show the points with $|a_D| < 0.1$ and $||b_D| - 1| < 0.1$ and in green $|b_D| < 0.05$ and $||a_D| - 1| < 0.05$. The SM-like scenario $\text{sgn}(C)\,(a_D, b_D) = (1, 0)$ is easily distinguishable from the $(0, 1)$ scenario. In fact, a measurement of ϕ_τ even if not very precise would easily exclude one of the scenarios. Obviously, all other scenarios in between these two will need more precision (and other measurements) to find the values of scalar and pseudoscalar components. The $\tau^+\tau^-h$ angle is related to α_2 as

$$\tan\phi_\tau = -s_\beta/c_1 \tan\alpha_2 \qquad \Rightarrow \qquad \tan\alpha_2 = -c_1/s_\beta \tan\phi_\tau\tag{15}$$
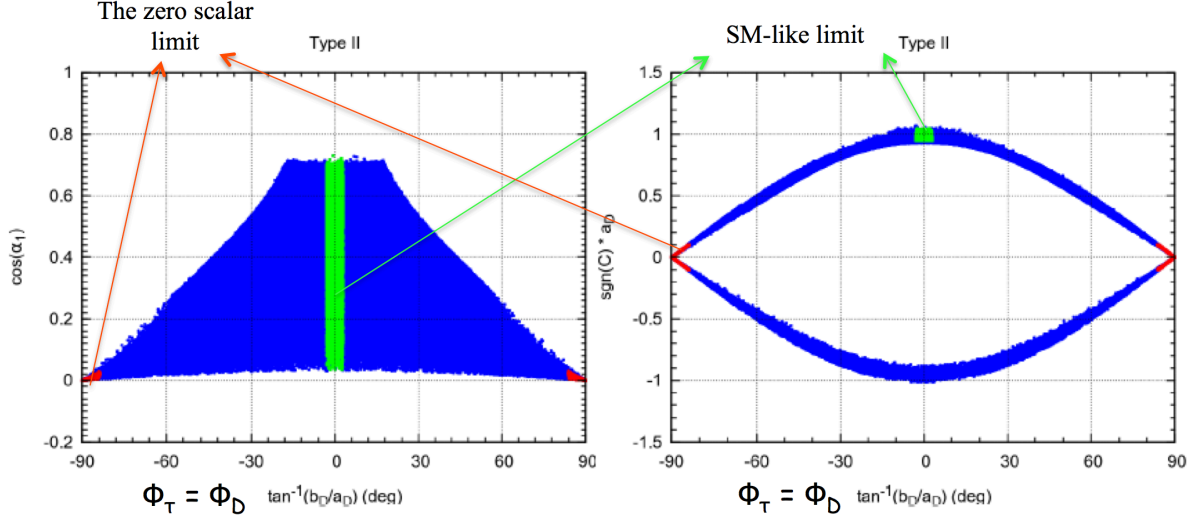
FIG. 5: Left: $\cos\alpha_1$ as a function of $\tan^{-1}(b_D/a_D)$ for Type II and a center of mass energy of 13 TeV with all rates at 10% (blue/black). In red/dark-grey we show the points with $|a_D| < 0.1$ and $||b_D| - 1| < 0.1$ and in green $|b_D| < 0.05$ and $||a_D| - 1| < 0.05$. Right: same, with $\cos\alpha_1$ replaced by $\mathrm{sgn}(C)\,a_D$.

and therefore a measurement of the angle ϕ_τ does not directly constrain the angle α_2 but rather a relation between the three angles. A measurement of ϕ_t and ϕ_τ would give us two independent relations to determine the three angles.

B. Constraints from EDM

The C2HDM, as all models with CP violation, are constrained by bounds arising from the measurement of electric dipole moments (EDMs) of neutrons, atoms and molecules. The parameter space of the C2HDM was analysed in [7, 10, 61–64] and ref. [7] found that the most stringent bounds are obtained using the results from the ACME Collaboration [65], except when cancellations among the neutral scalars occur. These cancellations were pointed out in [63, 64] and arise due to orthogonality of the R matrix in the case of almost degenerate scalars [9].

The scenarios we discuss have the couplings of the up-type sector (top quark) very close to the SM ones. Indeed, only the couplings in the down-type sector, namely tau lepton and the b-quark Yukawa couplings, are still allowed by data to have a vanishing scalar component. Due to the universality of the lepton Yukawa couplings the electron EDM also restricts the tau Yukawa. In a type II model this in turn also restricts the b-quark Yukawa of the SM-like Higgs. However, this is completely irrelevant in the Flipped model, where the charged leptons couple as the up-type quarks. We have shown in [14] that in a preliminary scan over the parameter space we have found points which pass all constraints including ACME's.

A dedicated study of the EDM contributions in the Type II C2HDM, where there are several sources of CP violation and where the partial cancellations of the various scalars is dully taken into account is in progress [66]. In addition, one should keep in mind that, as pointed out in ref. [10, 67], the future bounds from the EDMs can have a strong impact on the C2HDM. In the future, the interplay between the EDM bounds and the data from the LHC Run 2 will pose relevant new constraints in the complex 2HDM in general, and in particular for the scenarios presented in this work.

IV. CONCLUSIONS

We have discussed the interesting possibility of having a vanishing scalar component is some of the Yukawa couplings, namely the couplings of the lightest Higgs to down-type quarks and/or to leptons. These scenarios can occur for Type II, F and LS, and the pseudoscalar component plays the role of the scalar component in assuring the measured rates at the LHC. A direct measurement of the angles that gauge the ratio of pseudoscalar to scalar components is needed to further constrain the model. In particular, the measurement of ϕ_τ, the angle

for the $\tau^+\tau^-h$ vertex, will allow to either confirm or to rule out the scenario of a vanishing scalar, even with a poor accuracy. We have also noted that for the Type F, only a direct measurement of ϕ_D in a process involving the *bbh* vertex would probe the vanishing scalar scenario. Finally a future linear collider [68, 69] will certainly help to further probe the vanishing scalar scenarios.

Acknowledgments

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